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# *Macrocystis* Biomass, Quality, and Harvesting Effects in Relation to the Herring Spawn-On-Kelp Fishery in Alaska

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ABSTRACT: Giant kelp *Macrocystis* spp. is harvested for use in herring spawn-on-kelp, also called roe-on-kelp, fisheries, but information on the biology and ecology of kelp is limited for Southeast Alaska. A successful management plan must evaluate both the amount of kelp available for harvest and the recovery rates of kelp from harvest. In this study, estimating the amount of kelp available consisted of first estimating the total abundance of kelp in a survey area and second estimating the biomass of available and desirable kelp. The total biomass was estimated by surveying the surface area of kelp beds in selected regions on the west coast of Prince of Wales Island. Randomly selected "index beds" were surveyed to determine kelp density, and samples were measured and weighed to estimate the average weight of kelp fronds. About 2.04 x $10^5$ t of kelp were identified in the survey. The harvest of kelp for spawn on kelp is highly selective. We found that blades at least 14 cm wide and fronds with a high proportion of desirable blades were selected. The proportion of blades and fronds meeting these selection criteria were determined for the index beds, and the biomass of desirable kelp was estimated to be about 14% of the total kelp biomass in April. The growth in kelp canopy was rapid from March to April, with April canopies about 82% larger than March canopies. Even if kelp harvests increase 10 times over present levels, the harvest will represent only about 4.5% of the total estimated amount of kelp. Experimentally harvesting kelp canopies in March, April, or at both times had few significant effects. Kelp beds that were experimentally harvested at both times or only in April had shorter fronds and possibly fewer large fronds and fronds per plant. This experiment was monitored only one month after the last harvest, so there may not have been sufficient time for the cut kelp to recover.

## INTRODUCTION

Kelp beds are a conspicuous element of the outer coastlines of the northeastern Pacific Ocean (Foster and Schiel 1985). All kelps belong to the Laminariales (Phaeophyta), and some kelps, known as the canopy forming kelps, produce floats that buoy them to the surface. The giant kelp *Macrocystis* is a well known canopy forming genus that often grows in thick beds throughout the eastern Pacific Ocean. *Macrocystis* morphology consists of an attached holdfast with numerous fronds and numerous blades on each frond (Druehl 1984).

Kelp beds in nearshore ecosystems greatly increase habitat complexity and sedimentation rates and contribute large amounts of fixed carbon to the ecosystem (Duggins 1988; Duggins et al. 1989). *Macrocystis* kelp beds provide 15 $m^2$ of surface area for every square meter of substrate (Wing and Clendenning 1971), providing habitat for infaunal and epifaunal organisms (Duggins 1988). In addition, several species such as fish, mysids, and shrimp are abundant on or near *Macrocystis* fronds (Coyer 1984). Several juvenile and young of the year fish are found almost exclusively in kelp beds (Ebeling and Laur 1985;

**Authors:** PETER G. VAN TAMELEN is a fishery biologist with the Alaska Department of Fish and Game, Division of Commercial Fisheries, P.O. Box 240020, Douglas, AK 99824-0020. E-mail: pvt@fishgame.state.ak.us DOUG WOODBY is a fishery scientist with the Alaska Department of Fish and Game, P.O. Box 25526, Juneau, AK 99802-5526.

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Carr 1991). Kelp beds can also be significant sources of production, contributing large amounts of carbon in the form of attached plants, drift plants, particulate organic matter, and dissolved organic matter (Duggins et al. 1989). This carbon production is not limited to kelp beds because some unattached plants drift outside of the bed, with some pieces drifting miles from the source bed. In areas with lush kelp beds, about 50% of the total carbon in some fishes and birds is derived from kelp primary production (Duggins et al. 1989). Finally, kelp beds alter the flow of water in and around the bed (Jackson and Winant 1983). This altered flow results in higher sedimentation rates that may increase suspension feeding and recruitment of planktonic larvae. Altered flow caused by kelp beds may also increase the availability of planktonic food sources, such as barnacle cyprids, to resident kelp bed fish (Gaines and Roughgarden 1987).

There has been interest in harvesting kelp for various purposes since 1911 (Foster and Schiel 1985). In California about 100,000 metric tons of kelp are harvested annually for various products. Harvesting north of California has been sporadic with few large-scale commercial harvests. In British Columbia and Alaska *Macrocystis* kelp is harvested for use in the herring spawn-on-kelp (SOK) fishery. The average annual harvest of kelp for this fishery in Alaska is about 18 t and has been as high as 55 t. In this fishery, kelp blades are suspended from floats, either in enclosures or open to the sea, and herring then spawn on the suspended blades. The kelp blades with attached roe are then processed and sold. Because the price paid for the kelp blades with attached roe is partly dependent upon the quality of the kelp blade, harvesting kelp for SOK is highly selective. In particular, fronds with many wide blades are desirable.

Understanding the abundance and dynamics of giant kelp *Macrocystis* spp. is essential to manage the use of these algae for existing and emerging SOK fisheries and other uses. Information needed to properly manage kelp harvests in Alaska includes: 1) the amount of kelp that is available and desirable for harvest, and 2) the effects of harvesting on kelp beds and associated communities. Although resource managers almost always use weight to describe or regulate kelp harvests, the actual biomass of kelp beds is rarely assessed. Typically, the area covered by the kelp canopy is assessed using aerial photography. Once the exact methods are developed for aerial photography, or some other remote sensing technology, this procedure can be both fast and inexpensive, but developing the methods to estimate biomass from surface area can be initially expensive and time consuming. Procedures to estimate biomass from kelp bed surface area can be intricate (Foreman 1975). This study had 2 goals. First, we wanted to estimate the biomass of *Macrocystis* kelp available in southeastern Alaska and to ascertain how much of this kelp would be useful for SOK fisheries. For this initial survey, we developed methods to estimate kelp biomass that are fast and relatively easy to implement. Second, the short-term effects of harvesting on kelp beds and the ability of kelp beds to recover from harvests were assessed by use of a manipulative experiment.

## METHODS

### Total Biomass Estimates

Aerial surveys of kelp beds on the west coast of Prince of Wales Island were conducted between 23 and 29 March 1999 to identify and measure the surface area of kelp beds in selected areas (Figure 1). These areas were selected because of past kelp harvest patterns by SOK fishers and the presence of abundant kelp resources. The coastline was surveyed by an experienced Alaska Department of Fish and Game (ADF&G) herring spawn recorder using the same techniques that are used to map herring spawn. During the flight all significant *Macrocystis* kelp beds were marked on navigational charts, recording the approximate outline of each bed.

The resulting charts with marked kelp beds were analyzed to ascertain the surface area of kelp beds. The charts were scanned into digital format, and an image that included only the outlined kelp beds was produced. Using an image analysis program (Optimus), the scanned image was used to scale the kelp bed image, using landmarks of known length. An averaging procedure (5 x 5 pixels) was applied to the kelp bed image to eliminate small lines, numbers, and letters within the bed areas. The bed areas were then automatically outlined, and any remaining unwanted "holes" or other images were removed by hand. The image analysis program then determined the total area of "kelp beds," defined as both frond and water area within the bed perimeter.

To estimate the growth of kelp beds during the spring, several beds were photographed from an airplane during the March aerial survey and on 28 April 1999. The waters in Alaska have been divided into statistical areas by ADF&G, and about 20 areas west of Prince of Wales Island have kelp resources in them (Figure 1). One index bed was randomly selected from each statistical area, resulting in a stratified random

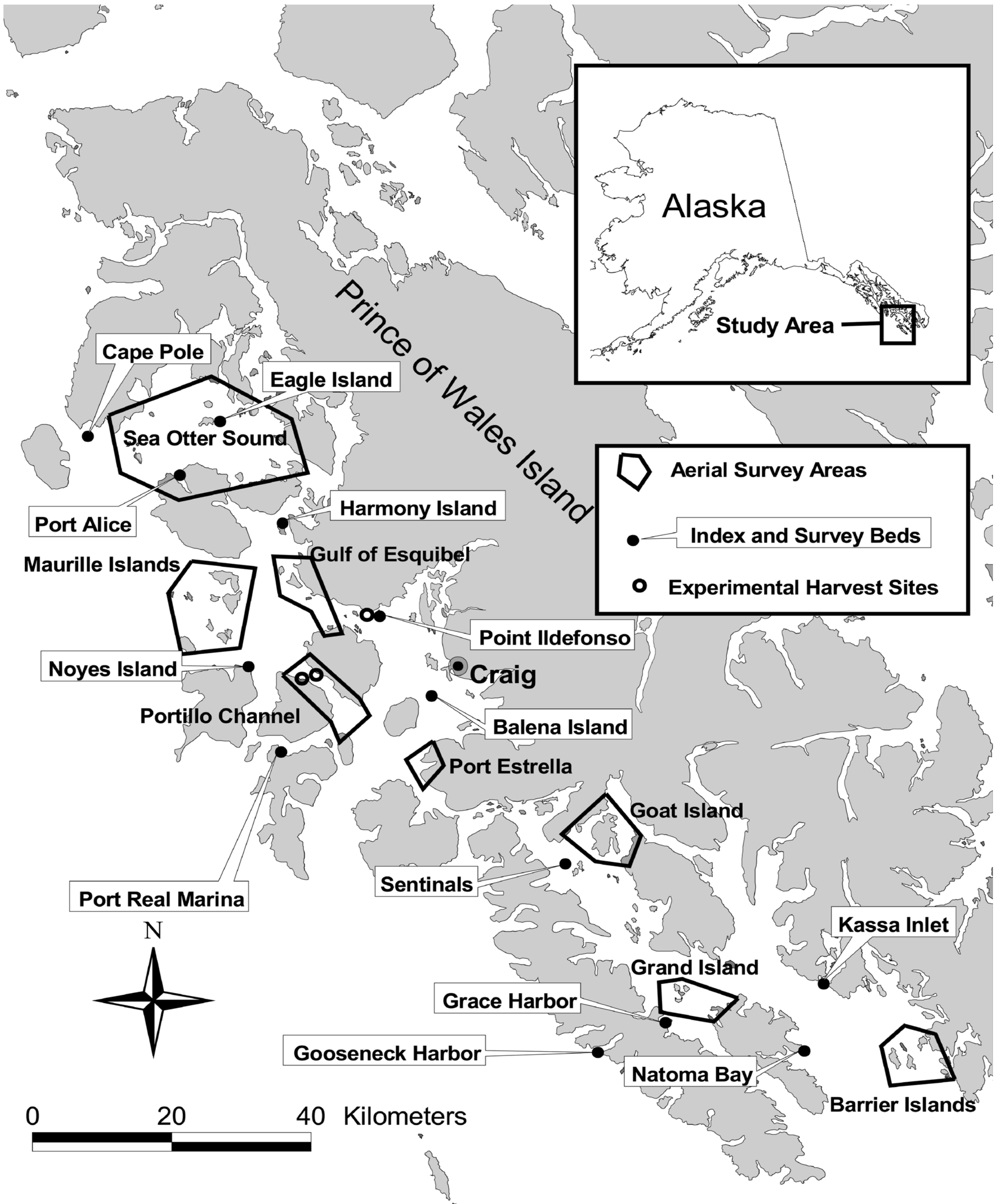


Figure 1. Map of the study area showing the location of surveyed regions, experimental harvest beds, the commercially harvested bed, and the index beds. The names of survey areas and index beds, in boxes, correspond to those found in Tables 1 and 3. The city of Craig on Prince of Wales Island is also shown.

sample of 11 kelp beds. To select a bed, a randomly placed point was located in each statistical area. The bed closest to the point and at least 20 $m^2$ in area was selected. Photographic methods were consistent between dates and the altitude (250–460 m) was recorded for each photograph. For each index bed, a pair of photographs, one each from March and April, were selected based upon similarity of photograph angle, direction, and altitude. The photographs were scanned into digital format and analyzed using the Optimus image analysis program. All canopy forming kelp fronds were outlined by hand using the image analysis program, and the total area of frond canopy was obtained.

The April photographs were calibrated using a photograph of a dock of known length taken from the same altitude. The March photographs were calibrated by measuring a distinctive object, usually a log or set of rocks, in the April photograph and using the same object as a scale in the March photograph. This procedure ensured that each pair of photographs was calibrated similarly. Calibration errors would be the same for each date, so between-date comparisons could still be made.

To estimate the length of fronds and the density of plants and fronds, 4 index beds, Balena Island, Eagle Island, Harmony Island, and Port Real Marina, were visited between 19 and 24 April. The visited kelp beds were determined largely by vessel routes and weather, and were restricted to the northern portion of the surveyed range. The density of kelp in each bed was estimated by scuba divers. Six transects were oriented perpendicular to the long axis of the bed and placed at even intervals along the length of the bed and extended through the entire bed. If transects were longer than 20 m, one 20-m long section was sampled either at the inside edge, outside edge, or the approximate center of the transect. The total length of the transect was recorded as well as the distance between transects so that total bed area could be calculated. To determine the average depth of the bed, start and end depths of each transect were recorded. Divers swam along transect lines and for each holdfast encountered within 1 m of the transect line counted the number of large (>1.5m) and small (<1.5m) *Macrocystis* fronds. Every 10$^{th}$ large frond was measured for length starting with the 10$^{th}$ frond.

To evaluate the selection of kelp and kelp beds by SOK fishers, the kelp bed that was used for the harvest of kelp for the Sitka Sound Open Harvest Platform Spawn-On-Kelp Test Fishery was monitored to allow comparison of the selected bed to other randomly selected beds. This bed was on the northeast side of Port Alice in Sea Otter Sound (Figure 1) and was surveyed by scuba in March just after the harvest and again in April as part of the index bed survey. The methods of survey were similar to the methods used for the index beds. The total harvest taken from this bed was also recorded.

To estimate the average weight of fronds, 22 fronds of varying length were weighed and measured on 27 April 1999. The fronds were cut into 1-m sections starting from the tip and working towards the base. The weight and section number were recorded for each section. At the base, the length of the final piece was also recorded. Thus, the total weight and length of each frond could be determined.

The total biomass was estimated by multiplying the total area of kelp beds, obtained from the aerial survey, by the average density of large fronds from index bed estimates and the average weight per frond. For this analysis, small fronds were ignored because they probably contributed little to the biomass due to low densities (<0.7/$m^2$) and small sizes. The average weight per frond was estimated by multiplying the ratio estimator of average frond weight/average frond length from the weighed fronds by the average length of fronds in the index beds. The relationship between frond length and weight was linear and had a zero intercept, so using a ratio estimator was appropriate. An estimate of the variance associated with the total biomass estimate was generated by combining variance estimates for both frond density and average frond biomass. Frond density averages and variances were weighted by bed size (Cochran 1977). The variance associated with the average frond biomass was calculated using methods to estimate variances from linear regression (Barnett 1991).

## Desirable Biomass

The desirability of kelp blades is based primarily upon blade width and overall condition (Richard Walsh, Home Port Seafoods, Washington, personal communication). Desirable blades are those that fit in the processing trays, about 18 cm wide, are free from holes, rips, silt, and epiphytes. To assess the desirability of kelp for SOK fisheries, the morphology of individual kelp blades was examined. Before any commercial harvest occurred, 3 fronds from each of 10 systematically located points in the Port Alice bed were collected. Three blades from each frond were chosen systematically with the 10$^{th}$, 15$^{th}$, and 20$^{th}$ blades being measured. The count started with the youngest free blade. The total length and maximum width of each blade were measured. In addition, the number of holes in the blade, the general condition of the blade, and the presence or absence of epiphytes and silt were recorded. The harvested kelp was also sampled. Forty haphazardly selected fronds were collected from the harvested kelp, and 3 randomly chosen blades were sampled. Knowing the morphology of blades before harvest and of harvested blades allowed the determination of the criteria used to select blades. For various widths of blades a selectivity index was calculated using harvested blades and blades available in the bed (van Tamelen and Stekoll 1996). The selectivity index was calculated as the difference between the proportion of blades used and available in each size class divided by the sum of these proportions.

To determine the proportion of desirable blades over the entire region, fronds were collected from the 4 visited index beds. Fronds were collected directly over dive transects. We attempted to collect a frond at 3 locations (inside edge of bed, outside edge of bed, and in the center of the bed) along each transect, but time constraints often reduced the sample size. Blades were then sampled in the same manner as the blades in the harvested bed.

Frond quality was assessed by comparing the number of desirable blades, out of the 3 sampled blades, among fronds from various locations. As with blade morphology, a selectivity index was used to compare the fronds available in the harvested bed before harvest to the fronds actually harvested. The proportion of desirable fronds over the entire region was then determined by using the sampled fronds from the index beds.

The biomass of desirable kelp was estimated by multiplying the total area of kelp beds by the density of desirable fronds and the average weight of fronds harvested. The density of desirable fronds was generated by multiplying the total frond density by the proportion of fronds that were available and the proportion of desirable fronds obtained from the index bed surveys. Available fronds were defined as those that were at least 5.3 m in length. This eliminated fronds that did not reach the surface (average depth of about 3 m) and have enough additional length to harvest (2.3 m obtained from the average length of harvested fronds). The variance component of the biomass estimate was obtained by combining variance estimates from the average weight of harvested fronds and the average density of available and desirable fronds.

## Effects of Harvesting

The goal of this experiment was to assess the effect of harvesting on kelp beds. Three kelp beds in the Craig area were used (Figure 1), and four 20-m transects were permanently established in each bed from the shallow side to the deep side. The kelp beds were selected arbitrarily and were all at least 20 m wide and 40 m long to accommodate the experimental design. Kelp density was estimated using the techniques described above for index beds for each study plot before any treatments were assigned. Those holdfasts that had only one small frond were considered juveniles.

All transects were marked, numbered, and surveyed between 24 and 25 March 1999. After the initial survey the experimental treatments were assigned to the transects. The 4 experimental treatments were: 1) March harvest (Early), 2) April harvest (Late), 3) March and April harvest (Early+Late), and 4) an unmanipulated control. Each treatment was randomly assigned to one of the 4 plots in each bed in a randomized block design. After treatments were assigned, plots with the Early and Early+Late treatments were harvested by cutting all fronds around the mean low water (MLW) mark. An 8-m wide swath centered on the transect line was harvested. The Late and Early + Late plots were similarly harvested after sampling in April. All plots were resurveyed using the standard dive measurements on 24–26 April and 15–16 June 1999. The experiment was statistically analyzed using a randomized block ANOVA model with site as the blocking

Table 1. The number of *Macrocystis* beds, average area of bed, and total area of all beds in 8 areas on the west coast of Prince of Wales Island.

| Area | Number of Beds | Area/Bed ($m^2$) | SD | Total Area ($m^2$) |
|---|---|---|---|---|
| Sea Otter Sound | 112 | 86,751 | 115,591 | 9,716,064 |
| Maurelle Islands | 166 | 66,557 | 90,088 | 11,048,501 |
| Gulf of Esquibel | 57 | 29,030 | 37,065 | 1,654,714 |
| Portillo Channel | 60 | 60,058 | 105,187 | 3,603,501 |
| Port Estrella | 17 | 25,229 | 32,496 | 428,885 |
| Goat Island | 18 | 34,985 | 34,977 | 629,727 |
| Grand Islands | 90 | 21,652 | 23,426 | 1,948,669 |
| Barrier Islands | 231 | 26,921 | 36,272 | 6,218,782 |
| Total | 751 | 46,936 | 76,629 | 35,248,843 |

factor. An $F$-max test was used to test the homogeneity of variances before statistical testing with ANOVA (Sokal and Rohlf 1995).

## RESULTS

### Total Biomass Estimates

From the aerial survey we identified 751 distinct beds from 8 regions on the west coast of Prince of Wales Island (Table 1). The average bed size over the surveyed area was 4.69 x $10^4$ $m^2$ ranging from 415 x $10^5$ to 8.86 x $10^5$ $m^2$. More than 35 million square meters or 3,520 hectares of kelp beds were surveyed (Table 1). This is only a partial survey of *Macrocystis* kelp on the west coast of Prince of Wales Island, and it represents about 60% of the kelp in this area. In addition there are kelp resources around Baranof Island, Sumner Strait, Kuiu Island, and Duke Island. In 1913 Cameron (1915) estimated about 18,332 hectares of kelp in southeastern Alaska, but only a small portion was *Macrocystis*.

Many characteristics of kelp populations at the index beds were evaluated using the information from scuba surveys (Table 2). The overall density of individual plants was about $0.34/m^2$. All index beds had more large fronds (mean of $2.45/m^2$) than small fronds ($0.46/m^2$). The number of fronds per plant ranged between 3.8 and 12.5 with an average of 9.3. Frond length was relatively constant between sites and averaged 6.1 m. Port Alice was excluded from the above numbers because this site was not randomly selected and is not representative of the entire kelp population. Port Alice was selected because the kelp harvesters wanted to get the best kelp with the least amount of effort, and the scuba surveys indicate that Port Alice differs from other kelp beds in several ways. The density of plants, the number of large fronds, and frond length were all greater at Port Alice compared to the index beds, but the density of small fronds and the number of fronds per plant at Port Alice were both within the range observed at index beds (Table 2). The average depth of the 4 index and 3 experimental harvest beds was 3.3 m below MLW, ranging from 1.3 to 6.1 m below MLW. The depths at Port Alice were greater than at the index beds ranging from 4.3 to 9.5 m below MLW and averaging 7.1 m below MLW.

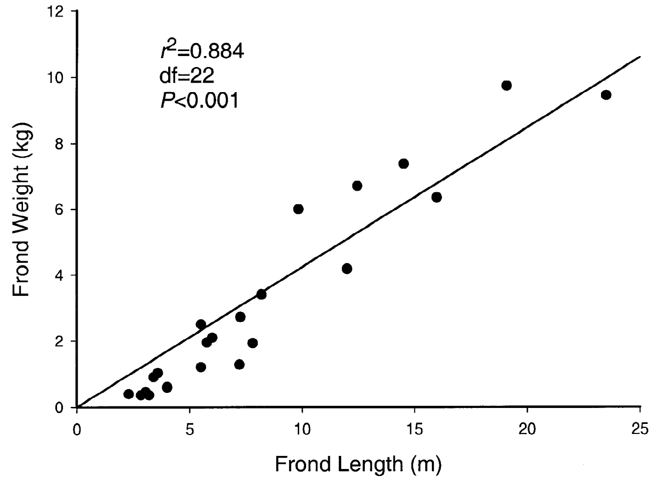


Figure 2. The relationship between *Macrocystis* frond length and weight. The results of the regression analysis are also shown.

There was a linear relationship between the length of a frond and its weight (Figure 2). Length was a good predictor of weight explaining 88% of the variation in frond weight. Because a plant of zero length cannot have any mass, the intercept must be zero. In this case a ratio estimate (average weight: average length) is a simple method to estimate average frond biomass from a sample of lengths. The ratio generated from the data in Figure 2 is 0.39 kg/m. The average

Table 2. The mean (standard deviation) density of *Macrocystis* plants, small fronds, large fronds, the number of fronds per plant, and frond length in surveyed index beds and the commercially harvested bed, Port Alice. The total bed area is given for each bed, and weighted averages are given with and without the Port Alice site.

| Site | Area of Bed ($m^2$) | Plants (no./$m^2$) | Juveniles (no./$m^2$) | Large Fronds (no./$m^2$) | Small Fronds (no./$m^2$) | Small:Large Fronds | Fronds/ Plant | Frond Length (m) |
|---|---|---|---|---|---|---|---|---|
| Port Alice | 89,516.0 | 0.50 (0.25) | 0.70 (0.87) | 3.71 (1.71) | 0.52 (0.21) | 0.15 (0.04) | 8.57 (2.05) | 9.49 (2.02) |
| Balena | 660.0 | 0.31 (0.23) | 0.03 (0.04) | 0.95 (0.74) | 0.20 (0.04) | 0.28 (0.18) | 3.79 (0.30) | 5.40 (1.56) |
| Eagle | 1,180.0 | 0.45 (0.17) | 0.23 (0.28) | 3.55 (1.29) | 0.65 (0.23) | 0.20 (0.09) | 12.50 (12.37) | 5.94 (0.63) |
| Harmony | 750.0 | 0.31 (0.15) | 0.06 (0.07) | 2.26 (1.56) | 0.35 (0.32) | 0.14 (0.10) | 8.31 (4.32) | 6.49 (2.07) |
| Port RM | 2,670.0 | 0.31 (0.20) | 0.04 (0.06) | 2.38 (1.12) | 0.48 (0.27) | 0.19 (0.05) | 9.52 (2.68) | 6.26 (1.69) |
| Average with Port Alice | | 0.50 (0.01) | 0.67 (0.02) | 3.64 (0.04) | 0.51 (0.00) | 0.15 (0.00) | 8.61 (0.04) | 9.30 (0.10) |
| Average without Port Alice | | 0.34 (0.01) | 0.08 (0.02) | 2.45 (0.18) | 0.46 (0.03) | 0.20 (0.01) | 9.29 (0.58) | 6.11 (0.08) |

length of fronds at the surveyed index beds was 6.1 m, so the average weight per frond was 0.39 kg/m × 6.1 m = 2.4 kg. The variance about this estimate was 0.065.

The overall biomass of kelp in the surveyed areas was calculated by multiplying the total area of kelp beds, the average density of large fronds, and average weight per frond. The estimated biomass of kelp in the areas surveyed was 2.04 x $10^8$ kg with an 80% confidence interval of ±4.38 x $10^7$ kg. Because we were only concerned with errors in estimates that were too low, we used 80% confidence intervals, yielding a 90% chance of our estimate being above the lower confidence bound. Based upon the weight per unit area, this estimate corresponds to "very thin" beds reported by Cameron (1915) and the June harvest yields of Coon (1982).

## Desirable Biomass

The harvest of kelp for the spawn-on-kelp fishery was highly selective with both blades and fronds being chosen for high quality. For the 1999 SOK fishery, kelp blades in the 14–16-cm size range or higher were selected relative to the blade widths available in the bed (Figure 3). At Port Alice, the distribution of blade widths in the bed showed little change between March and April (Figure 3). The width of blades varied among the index beds (Figure 4). Eagle Island had narrow blades with few blades wider than 16 cm and few blades in the harvested size range. Blades wider than 16 cm were often torn and broken. A broad range of blade widths at Harmony Island spanned the range of harvested widths. The few samples taken at Balena Island indicated that most blades were 14–18 cm wide. At Port Real Marina, blades were very wide with almost all blades wider than 16 cm, but most blades at this site were covered with fine silt or damaged by grazers.

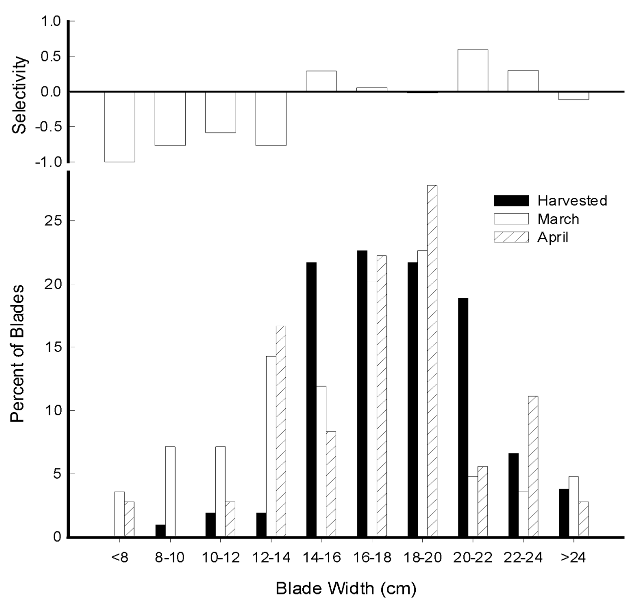


Figure 3. The proportion of *Macrocystis* blades of various widths of harvested kelp, kelp in the Port Alice bed before harvest (March), and later in the spring (April). Selectivity indices for the different blade widths using the harvested and March data are shown in the upper graph. Negative and positive selectivity indices indicate avoidance and selection, respectively.

Table 3. The estimated area of the *Macrocystis* canopy in southeastern Alaska in March and April at the index beds estimated from aerial photographs. The percent change from March to April is also given.

| | Canopy Area ($m^2$) | | |
|---|---|---|---|
| Site | March | April | % Increase |
| Balena Island | 50,395 | 68,160 | 35 |
| Cape Pole | 12,980 | 21,466 | 65 |
| Eagle Island | 10,727 | 13,043 | 22 |
| Gooseneck Harbor | 3,518 | 14,484 | 312 |
| Grace Harbor | 3,182 | 3,827 | 20 |
| Harmony Island | 5,049 | 8,443 | 67 |
| Kassa Inlet | 16,349 | 28,447 | 74 |
| Natoma | 1,576 | 4,983 | 216 |
| Noyes Island | 32,694 | 45,720 | 40 |
| Point Ildefonso | 2,790 | 3,305 | 18 |
| Port Real Marina | 20,119 | 22,667 | 13 |
| Sentinals | 2,172 | 4,365 | 101 |
| | | Mean | 82 |
| | | SD | 91 |

Most fronds used in the test fishery had 2 or 3 desirable blades of the 3 sampled, and these higher quality fronds were harvested more frequently than their availability in the Port Alice bed (Figure 5). In the index beds, 38.7% of fronds had 2–3 desirable blades. Most of these desirable fronds were found at one index bed (Harmony Island).

The estimated density of available fronds was 1.26 available fronds/$m^2$, calculated as the average frond density, 2.45 fronds/$m^2$ (Table 2), multiplied by the proportion of fronds longer than 5.3 m, 0.5125. The proportion of desirable fronds in the index beds was 38.7%. Therefore the density of available desirable fronds was 1.26 available fronds/$m^2$ multiplied by 0.387, which equaled 0.486 available desirable fronds/$m^2$. The average weight of harvested fronds was 1.73 kg/frond. Thus, the biomass of available desirable fronds in the surveyed area in April 1999 was 2.96 x $10^7$ kg with an 80% confidence interval of ±2.02 x $10^7$ kg, or about 14% of the total kelp biomass.

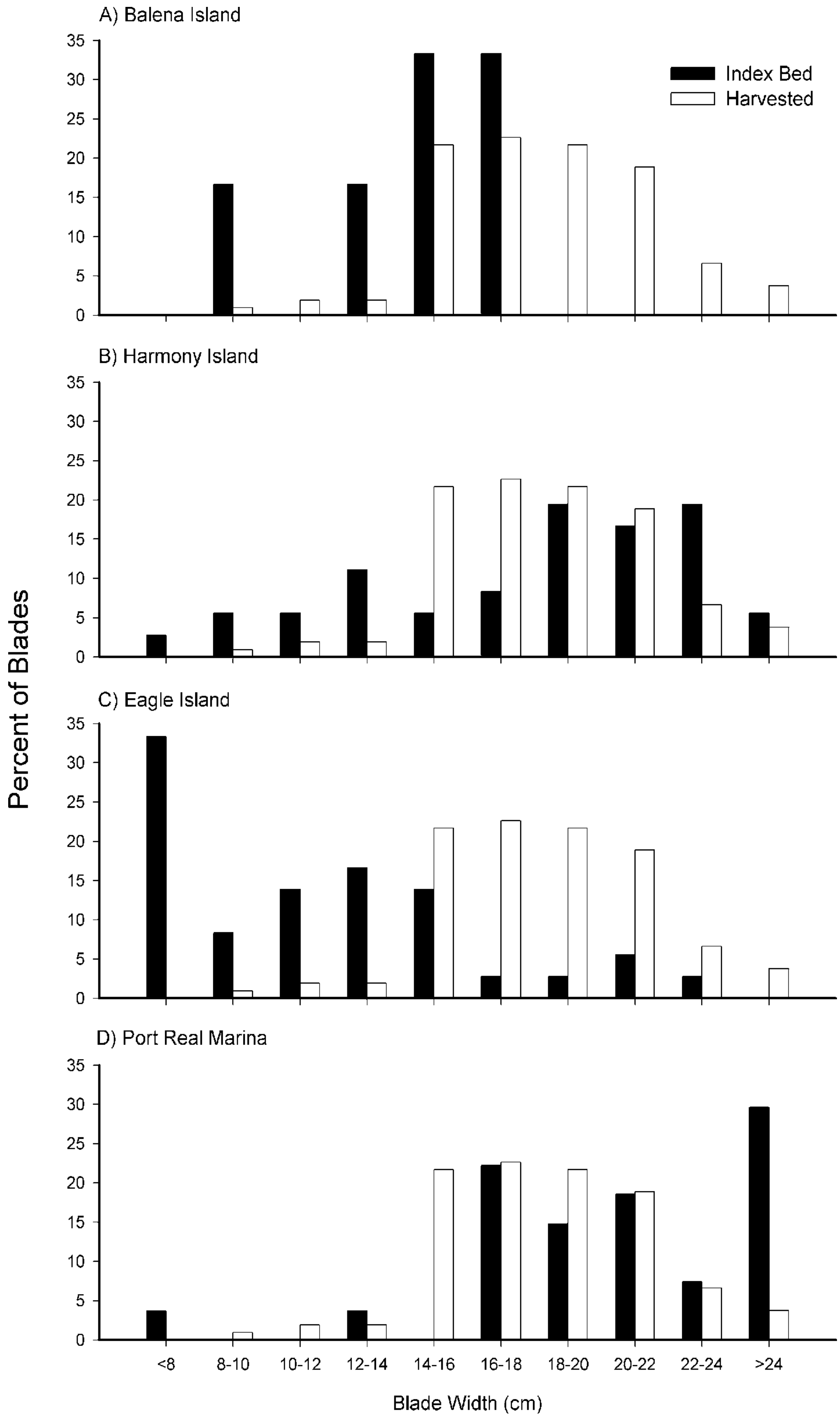


Figure 4. Size distribution of *Macrocystis* blade widths at the index beds compared to the harvested kelp.

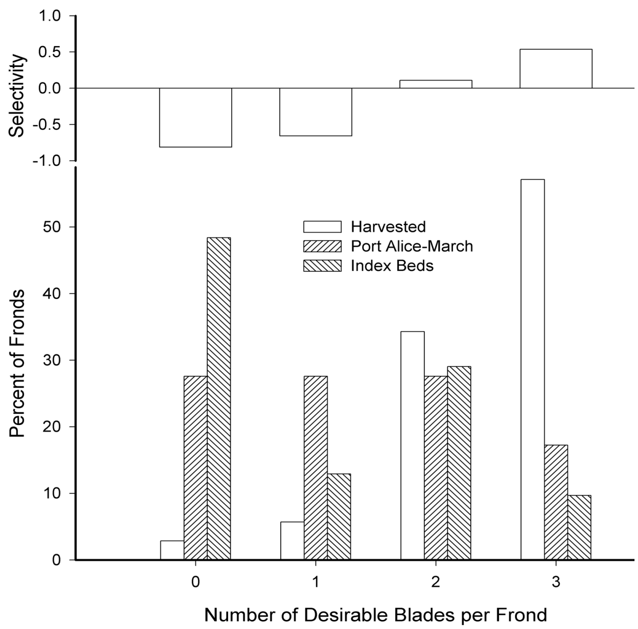


Figure 5. The proportion of *Macrocystis* fronds with 0, 1, 2, or 3 desirable blades at the Port Alice site before harvest, at the index beds, and harvested from the Port Alice bed. Selectivity indices for the various fronds using the harvested and March data are shown in the upper graph. Negative and positive selectivity indices indicate avoidance and selection, respectively.

The surface area of all index beds increased from March to April (Table 3). The percent increase in surface area ranged from 12% to 311% with a mean increase of 82%. Thus, beds in March averaged about 45% smaller than beds in April. If a linear relationship exists between surface area and biomass, then the April biomass estimate can be appropriately reduced to obtain a March biomass estimate. Decreasing the April biomass estimate by 45% resulted in a total biomass in March of 1.12 x $10^8$ kg and a desirable biomass in March of 1.63 x $10^7$ kg.

## Effects of Harvesting

Over 3 months, harvesting *Macrocystis* plants or beds had few detectable effects (Figure 6). To account for variation in the starting densities or lengths, differences between the June sampling date and the preharvest March sampling date were statistically analyzed (Table 4). All of the raw data met the ANOVA assumption of homogeneity of variance, so raw data was used in the analyses. Average frond length was significantly lower on plots harvested later in the season compared to the early harvest or control plots (Figure 6f; Table 4). Also decreases in the density of large fronds and the number of fronds per plant in the plots harvested in both March and April were marginally significant (Figure 6c, e; Table 4). Harvesting had no detectable effects on the densities of plants, small fronds, or juveniles (Figure 6a, b, d; Table 4).

# DISCUSSION

Kelp resources in Alaska are abundant relative to the current and potential harvest of kelp for herring spawn-on-kelp fisheries. The estimated total abundance of kelp in the areas surveyed was more than 200 million kilograms. If the current SOK fishery of about 200 permits increased 10 fold and each permit used 4,536 kg (5 tons), a typical value obtained from a test fishery in 1999, the total annual harvest of kelp would be just over 9 million kilograms or about 4.5% of the total biomass. Thus, based upon the results of this limited survey there appears to be enough kelp to support a large spawn-on-kelp fishery.

The total kelp biomass was estimated from aerial surveys of the extent of kelp beds, estimates of frond

Table 4. Statistical results of the experimental harvest of *Macrocystis* and the measured variables. Small fronds are those less than 1.5 m, and large fronds are longer. Juveniles are plants with one frond less than 1.5 m. The *F*/MSE columns are composed of the *F*-ratios for site and harvest treatment and the mean square error. Full ANOVA tables can be reconstructed from the supplied information.

| Variable | Source | df | *F*/MSE | *P* value |
|---|---|---|---|---|
| Plants | Site | 2 | 3.110 | 0.118 |
| (no./m$^2$) | Harvest | 3 | 0.670 | 0.600 |
| | Error | 11 | 0.403 | |
| Small Fronds | Site | 2 | 3.780 | 0.087 |
| (no./m$^2$) | Harvest | 3 | 0.670 | 0.600 |
| | Error | 11 | 1.000 | |
| Large Fronds | Site | 2 | 2.690 | 0.147 |
| (no./m$^2$) | Harvest | 3 | 3.840 | 0.076 |
| | Error | 11 | 0.808 | |
| Juveniles | Site | 2 | 0.170 | 0.848 |
| (no./m$^2$) | Harvest | 3 | 0.920 | 0.485 |
| | Error | 11 | 0.127 | |
| Fronds per Plant | Site | 2 | 1.090 | 0.393 |
| | Harvest | 3 | 3.510 | 0.089 |
| | Error | 11 | 2.150 | |
| Frond Length | Site | 2 | 1.240 | 0.353 |
| (m) | Harvest | 3 | 7.270 | 0.020 |
| | Error | 11 | 1.040 | |

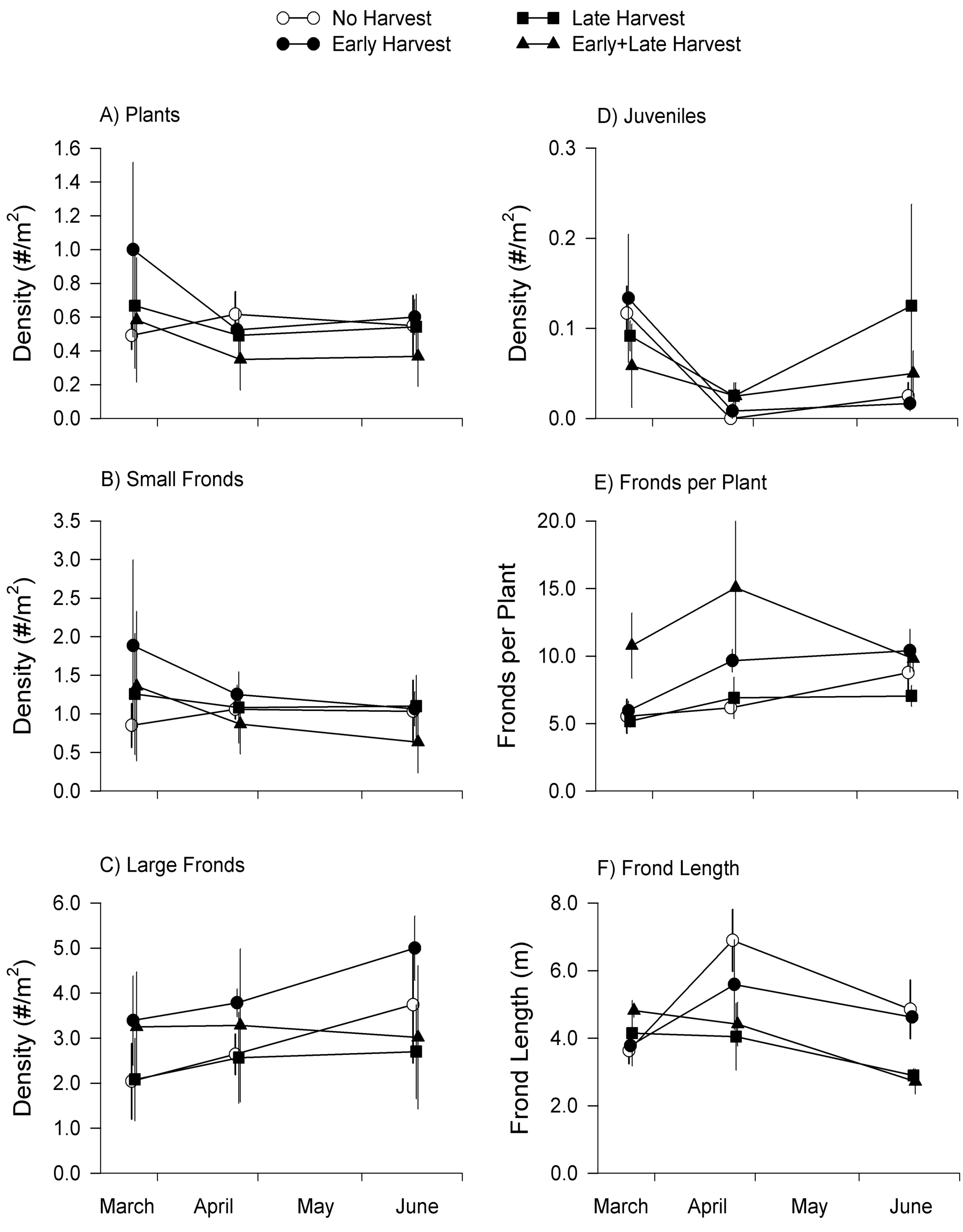


Figure 6. Results of the experimental harvest of *Macrocystis* in southeastern Alaska on the density of plants, small fronds, large fronds, juveniles, the number of fronds per plant, and the frond length. The early and late harvests occurred in March and April. Error bars represent one standard error of the mean.

densities, and estimates of frond weight. Each of these components can contribute to errors in the biomass estimation. Any error inherent in the aerial survey methods was not quantifiable, so the estimate of total kelp bed area was treated as a census with no error in the analysis. In recording the extent of individual beds during the surveys the size of some beds may have been overestimated and others underestimated. Also, some *Nereocystis* beds may have been misidentified as *Macrocystis* and included in the survey, resulting in an overestimate of *Macrocystis* area. Conversely, some *Macrocystis* beds may have been identified as *Nereocystis* beds, resulting in underestimation of *Macrocystis* bed area. Without performing multiple surveys over a single area, it is difficult to estimate these sources of error.

Aerial photography from belly- or wing-mounted cameras using infrared film would reduce errors in canopy area estimation and has been used in British Columbia (Foreman 1975). The KIM-1 method of kelp inventory outlined by Foreman (1975) could be implemented in Alaska, but the methods should be revised to take advantage of more recent technological advances in image analysis and computers. Problems with species identification can be eliminated by performing the photography at a low enough altitude to ensure positive identification. All potential problems associated with aerial photography including photographic methods, weather dependency, flying speeds and altitudes, and image analysis need to be resolved before any large-scale use of aerial photography to estimate kelp bed area is implemented. Once these problems have been resolved, aerial photography could be used to rapidly generate extensive and accurate estimates of kelp bed area. Our methods, however, provided an estimate of kelp abundance in a relatively short time frame of 3.5 months from study initiation to initial reporting.

The error estimates for total biomass were obtained from a combination of the estimates for frond density and frond weight. Frond density estimates made up about one-third of the error estimate for total biomass, and the frond weight estimates accounted for the remaining error. The disparity between the error contributions of frond density and frond weight indicate that relatively more effort should be devoted to sampling frond weight. The precision of the sampling, however, was within 22% of the mean with 80% confidence intervals, indicating a reasonable estimate of the total kelp biomass in the surveyed area.

Estimating the amount of desirable kelp for the SOK fishery proved difficult. To be desirable a frond should have a high proportion of blades that are at least 14 cm wide and in good condition. Because blade and frond quality can only be assessed by field sampling, and the estimates for the proportion of desirable kelp reflects sampling from only 4 beds, the precision of the biomass of desirable kelp was quite low (±68%). More beds need to be surveyed to make more accurate estimates of desirable biomass.

Blade morphology of many algae has been shown to be dependent upon water movement (Norton 1969; Druehl 1978; Norton et al. 1982; Koehl and Alberte 1988). In low flow areas, blades generally have more undulations, are larger, wider, and are not split. *Macrocystis integrifolia* shows similar plasticity in growth form (Druehl 1978; Hurd et al. 1997). This plasticity in growth form is highly functional. Undulations dramatically increase drag forces, resulting in higher blade mortality in high flow regimes, but in low flow areas the undulations serve to increase nutrient uptake by initiating turbulent flow around the blade (Hurd et al. 1997). Also, larger blades are better able to gather light but cannot withstand the drag and accelerational forces exerted by wave action (Denny et al. 1985). Because *Macrocystis* blade morphology is dependent upon wave exposure and currents (Druehl 1978; Hurd et al. 1997), it may be possible to predict the quality of blades in kelp beds if the exposure of the bed is known. The water flow regime for an area depends upon many factors including tides, fetch, bottom topography, local land masses, and wind. Blade morphology possibly could be related to a derived exposure index by sampling blades and fronds in a variety of kelp beds varying in exposure. The condition of kelp blades may also be indirectly dependent upon water flow. Waves may limit the activities of herbivores (Menge and Sutherland 1976) and may prevent fouling organisms from colonizing. Thus, in very protected waters, at Port Real Marina for example, kelp blades may be wide, but their quality may be low due to severe grazing and fouling. We observed numerous grazers and fouling organisms on the blades at Port Real Marina. At the exposed Eagle Island site, few grazers or epiphytes were observed on the sampled kelp blades.

The canopy area of kelp beds in California declines in winter and reaches a maximum in late summer (Dayton 1985; Foster and Schiel 1985; Harrold and Reed 1985; Watanabe and Harrold 1991). Thus, kelp canopies increase in area during the spring months. The extent of kelp canopies in our study increased by an average of about 82% from March to April. Because the earliest herring spawn is in March in Sitka Sound, the kelp available for early herring SOK fisheries was much less than that available for later herring fisheries in April and May.

A temporal change in kelp composition has occurred since the early survey of kelp in southeastern Alaska (Cameron 1915). Many of the current *Macrocystis* beds were *Nereocystis* beds in 1913. Harrold et al. (1988) observed similar changes in species composition of kelp beds and attributed this to the reintroduction of sea otters, which reduced sea urchin abundance. Because *Nereocystis* is more resistant to grazing by sea urchins than *Macrocystis,* it became more abundant when sea otters were removed and sea urchins were abundant. When sea otters were reintroduced, *Macrocystis* replaced *Nereocystis* at the more-protected sites (Dayton et al. 1984; Harrold et al. 1988). A similar process is probably occurring in Southeast Alaska because the current sea otter distribution corresponds to areas where beds have changed from *Nereocystis* to *Macrocystis* since 1913.

The effects of harvesting kelp have been examined in numerous studies. Of the studies surveyed here, 5 were done in *M. pyrifera* beds in California (Miller and Geibel 1973; Kimura and Foster 1984; Barilotti et al. 1985; Barilotti and Zertuche-Gonzalez 1990) and Chile (Santelices and Ojeda 1984), and 2 were done in British Columbia in *M. integrifolia* beds (Coon and Roland 1980; Coon 1982; Druehl and Breen 1986). Of these 7 studies, all but one (Coon and Roland 1980; Coon 1982) had flawed experimental designs or statistical analyses. None of the remaining 6 studies were replicated, and each harvest treatment was represented by a single area or bed and compared to a single control area. In all but one of these unreplicated studies inferential statistics were applied and thus were pseudoreplicated (Hurlburt 1984). The remaining study (Druehl and Breen 1986) did not use statistics in their study, and differences were judged by intuition and experience. The results of these studies are frequently contradictory; for example, harvesting kelp has shown increases, decreases, or no change in kelp growth, holdfast growth, frond production, and plant survivorship. Hence, the results must be interpreted with caution.

Of the studies that examined recruitment, defined as the appearance of young individuals in a population, all found that recruitment increased when kelp was harvested (Miller and Geibel 1973; Kimura and Foster 1984). The only significant effect observed in our study was a decrease in the average length of fronds in harvested areas. Our lack of significant results does not necessarily indicate no effect of harvesting, but it may be a result of low replication of treatments. Also, the experimental beds have only been monitored once, 2 months after harvest, so any long-term effects have not been determined. By law, kelp fronds can be cut no lower than 0.3 m (1 ft) below the surface of the water, but there is no limit on the number of fronds that can be cut in a bed (ADF&G regulation 5 AAC 37.300[b]). Thus, this experiment implemented the maximum harvest possible under current regulations by cutting all fronds 0.30 m below the water surface. The lack of detectable effects indicate that the more limited harvest by the SOK industry may have little effect on kelp beds. Although SOK fishers may concentrate their efforts in beds with abundant desirable kelp, our observations indicate that they will rarely take more than about 20% of any one bed. At this stage, much of the high-quality kelp has been harvested, and it is not worth the effort to sort through the remainder.

This study provided some preliminary answers to the questions of 1) how much *Macrocystis* is available and desirable for harvest in selected areas of southeastern Alaska, and 2) what are the short-term effects of a harvest on *Macrocystis* beds? The more than 2.04 x $10^5$ t of *Macrocystis* kelp identified in this study appears to be sufficient to support SOK fishing for all of Alaska. The maximum amount of kelp that could be used in SOK fisheries in Alaska is less than 5% of this amount. If the kelp harvests are not concentrated in any one bed or area, the probability of depleting the kelp resource is low. In addition, the effects of the maximum harvesting allowed are apparently minimal. To fully assess the abundance of all *Macrocystis* resources in Alaska, a more complete survey should be performed. If a good photographic system is developed, a thorough survey should be practical. In addition, kelp density should be monitored yearly on a few representative kelp beds to ascertain yearly fluctuations in kelp density. Kelp beds often have dramatic yearly changes in abundance and density that are related to El Niño events (Dayton et al. 1984; Dayton and Tegner 1984; Tegner and Dayton 1987, 1991; Dayton et al. 1992).

Increasing the demand for high-quality kelp may result in conflicts among users for more desirable kelp. Of the 2.04 x $10^5$ t of kelp surveyed, only about 14% was deemed desirable to the SOK industry. Assuming that the number of SOK permits increased 10 fold to 2,000 and all harvested 4.536 t (5 tons) of kelp for herring SOK, then a maximum potential statewide harvest for SOK would be 9,072 t. A total Alaskan harvest of 9,072 t would represent about 30% of the estimated amount of desirable kelp available; however, the estimate for the amount of desirable kelp is very uncertain. If the low estimate of desirable kelp, about 9,470 t, is used, an increased harvest level of 9,072 t would result in a harvest of almost 100% of the desirable kelp. At this harvest rate, users will almost certainly find desirable kelp hard to locate. The estimate for the amount of desirable kelp needs to be improved. Many kelp beds need to be surveyed and the kelp blades should be measured. The width of kelp blades appears to vary little at a site over the season, so a kelp bed can be evaluated at any time during the spring and early summer.

Based upon the published literature and the limited experiment described here, limited harvests of kelp beds would have few lasting effects. Given the high growth and production rates of *Macrocystis* elsewhere (Lobban 1978a, 1978b; Coon 1982; Wheeler and Druehl 1986; Jackson 1987), it is reasonable to expect that kelp recovery from harvesting in spring should be completed by the end of summer. More experimental evidence is needed to support this conclusion. Specifically, the effects of harvesting the same bed every year, as well as harvesting only once, on kelp beds and associated communities need to be evaluated. Yearly partial removals of a kelp canopy can potentially result in the deforestation of the kelp bed by the following mechanism. If reductions in kelp canopy result in decreased drift algal abundance (Harrold and Reed 1985; Druehl and Breen 1986; Tegner and Dayton 1991), sea urchins may begin to actively forage rather than collecting drift algae (Dean et al. 1984; Ebeling et al. 1985; Harrold and Reed 1985; Tegner and Dayton 1991). Actively foraging sea urchins can completely deforest a kelp bed in a matter of months, creating an urchin barren (Watanabe and Harrold 1991). Because of this potential for large changes in a kelp bed community and consequent impacts to surrounding communities, we suggest that caution should be used when harvesting large amounts of kelp or harvesting annually in the same bed despite the apparent abundance of *Macrocystis*.

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